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A Review of Visual Soil Evaluation Techniques for Soil Structure

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Running Title: Rev. of soil structure VSE Techniques

Summary

Soil structure forms a key component of soil quality and its assessment by semi-quantitative Visual Soil Evaluation (VSE) techniques can help scientists, advisors and farmers make decisions regarding sampling and soil management. VSE techniques require inexpensive equipment and generate immediate results that correlate well with quantitative measurements of physical and biochemical properties, highlighting their potential utility. We reviewed published VSE techniques and found that soils of certain textures present problems and a lack of research into the influence of soil moisture content on VSE criteria. Generally, profile methods evaluate process interactions at the point scale, exploring both intrinsic aspects and anthropic impacts. Spade methods focus on anthropogenic characteristics, providing rapid synopses of soil structure over wider areas. Despite a focus on structural form, some methods include criteria related to stability and resiliency. Further work is needed to improve existing methods regarding texture influences, on-farm sampling procedures and more holistic assessments of soil structure.

Keywords: visual soil examination, soil quality, soil structure

Introduction

Soil structure is a key component of soil quality (Askari *et al.*, 2015; Mueller *et al.*, 2013), influencing and influenced by soil chemical and biological properties (daSilva *et al.*, 2014; Askari *et al.*, 2015). Current concerns over soil resource degradation (Koch *et al.*, 2013), emphasise the importance of assessing soil structure (Mueller *et al.*, 2013). Semi-quantitative procedures for structure evaluation using visual and tactile assessment are receiving increased attention (Ball *et al.*, 2013) notably regarding impacts of current agricultural practices (Batey, 2009), reduced tillage strategies (Giarola *et al.*, 2013) and agri-environmental considerations (Newell-Price *et al.*, 2012). Soil has been visually assessed for millennia (Batey, 2000) and Visual Soil Evaluation (VSE) techniques (Ball and Munkholm, 2015) offer repeatable procedures for examining structural morphology for soil quality assessment (Mueller *et al.*, 2013). Correlations between VSE techniques and quantitative soil measurements have been widely described (McKenzie, 2001; Mueller *et al.*, 2009; Pulido Moncada *et al.*, 2014a) including indicators of soil physical quality (Guimarães *et al.*, 2013; Pulido Moncada *et al.*, 2014b) and bio-chemical quality (Askari *et al.*, 2015; daSilva *et al.*, 2014). Compared to quantitative measurements, VSE techniques provide rapid easily interpreted results using inexpensive equipment, making them widely accessible (Guimarães *et al.*, 2013; Ball *et al.*, 2007; Batey, 2000).

Due to increased interest in VSE techniques and the numerous methods in use, this review will outline the in-field procedures most widely described (according to published, English language literature from 1940 onwards), discuss VSE methodology and synthesise strengths, weaknesses and complimentary aspects between specific procedures, thus identifying improvements.

An outline of in-field methods

VSE techniques can be categorised into spade (Tables 1 and 2) and profile methods (Boizard *et al.*, 2005; Mueller *et al.* 2009). The former require soil sample blocks to be examined after extraction by spade (Tables 1 and 2), evaluating structural state up to 50cm depth, over wide areas. The latter, founded on soil survey principles (McKeague *et al.*, 1986; Batey, 2000), require examination of soil profiles to ≈ 1.5m in soil pits, generally excavated mechanically (Table 3), providing detailed information at point scale.

Spade methods

Görbing's (1947) Spade Diagnosis, the first published technique, focuses on anthropic impacts on structure and crop growth, qualitatively assessing soil structure, rooting and moisture content. The Peerlkamp (1959) method, the first semi-quantitative single-score procedure, together with Görbing's method, formed the foundation of more recent procedures. The Peerlkamp method focuses on anthropic impacts on structure (Boizard *et al.*, 2005). A sample block extracted to 15cm is rapidly scored between 1 and 10 considering aggregate shape, size and porosity, particle cohesion and root development. Layers can be assessed separately (Peerlkamp, 1967). The Werner Method (Werner and Thämert 1989) examines soil physical state in terms of crop growth, assessing individual layers up to 50cm. Properties including aggregate size, shape, intra-aggregate fissures, aggregate face width and bio-pores each receive a score

(Mueller *et al.*, 2009). All three methods require the manual break-up of sample blocks to expose aggregates, a key process in all spade methods.

Drop tests, which involve dropping sample blocks from a defined height onto a hard surface to expose aggregates, are also used. The Diez method (see Mueller *et al.*, 2009), first described in the late 1990's, incorporates a drop test from ≈ 1m. Exposed aggregates are then assessed by hand. The method can assess anthropic impacts to 40cm (Diez *et al.*, 2012). Soil surface condition, topsoil and subsoil structure along with rooting, redox morphology, organic matter decomposition, macro-porosity and the transition layer between topsoil and subsoil are assessed with reference to a manual, with the option of generating a single summarising score (R. Brandhuber, personal communication).

Beste (1999) developed an extended version of Görbing's Spade Diagnosis, which assesses structure for rooting and soil biota requiring the manual aggregate exposure. It incorporates a scoring system while also assessing aggregate water stability and includes quantitative measures. Layers are assessed with an emphasis on surface crust formation, silting and presence of worm casts (0-1cm depth), aggregate shape and quantity of granular or angular aggregates (0-15cm and 15-30cm depth) along with aggregate shape and inter-aggregate porosity (30-40cm depth).

Munkholm's (2000) Spade Diagnosis was founded on Preuschen's and Sobelius' Spade Diagnosis, both modified versions of Görbing's (1947) method. Layers within a sample block taken to 30cm are examined. Boundaries, texture, aggregate type, size and grade, rupture resistance, porosity, rooting, soil fauna and organic matter decomposition, are described in detail to support soil management. A drop test is included to determine the degree of aggregation, but most of the assessment is by manual manipulation (Table 2).

The Visual Soil Assessment (VSA) method (Shepherd 2000; 2009) captures intrinsic quality factors and anthropic impacts on soil structure. Plant and soil indicators are included and treated separately. For the main soil structure indicator, a drop test on an 8,000cm^3 sample block, generally extracted from the topsoil. Exposed aggregates are arranged by size on a flat surface for visual estimation of aggregate size distribution by comparison with reference photographs included in a field manual. Additional visual procedures are included for potential carbon sequestration and nutrient loss through leaching, run-off and gaseous emissions (Shepherd 2010a). For soil quality the "*VS* score" is the sum of individual weighted indicator scores for soil texture, structure, colour and smell, mottling, macro-porosity, the presence of earthworms, potential rooting depth, surface ponding, surface crusting and cover, and erosion.

The Soil Quality Scoring method (Ball and Douglas, 2003) is based on Munkholm's (2000) diagnostic principles along with Beste's (1999) scoring criteria, assesses soil physical fertility to 30cm through manual exposure of aggregates. Focusing on anthropic impacts, surface condition, soil structure (by layer) and crop rooting are assessed with reference to explanatory notes. The structure score is summed and weighted by layer depth.

The FAL Method (Hasinger *et al.*, 2004) includes a drop test on individual layers from the upper 45 cm (Boizard *et al.*, 2005). With an emphasis on anthropic impacts on structure, aggregate size distribution is determined manually with smaller aggregates sieved from 20mm to 0.2mm. With reference to images and a coding key, aggregates are classified and the mean weight diameter and mean weight score are determined for each soil layer (Boizard *et al.*, 2005).

In 2007, three spade methods were published. The Visual Soil Structure Quality Assessment (VSSQA) described by Ball *et al.* (2007), was based on the Peerlkamp method and subsequently renamed Visual Evaluation of Soil Structure (VESS) following refinement (Guimarães *et al.*, 2011). VESS examines anthropic impacts on structure and is accessible to non-experts. From the top 25cm depth, the size, shape and visible porosity of aggregates are evaluated using an illustrated scoring key applied to individual layers. The weighted average gives an overall "*Sq*" score, similar to the system devised by Ball and Douglas (2003).

The 'Thinksoils' manual, developed by the United Kingdom's Environment Agency (2007), includes instructions on conducting in-field assessment, emphasising erosion and runoff risk. Soil surface, topsoil and subsoil structure, macro-porosity, aggregate type and packing density along with plant and root growth are qualitatively examined. (Environment Agency, 2010). The M-SQR method (Mueller *et al.,* 2007) explores intrinsic soil quality and anthropic impacts to assess long-term soil quality for cropping or grazing. It is not exclusively an in-field procedure (therefore omitted from Tables 1 and 2), as regional climatic and soil survey date are incorporated (Mueller *et al.,* 2013). An overall "*SQ* score" of between 1 and 100 is generated from structural evaluation along with assessment of inherent soil properties that limit productivity (e.g. stoniness) and identifying "hazard" factors that limit soil quality (e.g. salinization).

Profile methods

Le Profil Cultural, originally developed by Hénin *et al.* (1960) and described by Manichon (1987), evaluates anthropic impacts (Roger-Estrade *et al.*, 2004; Peigné *et al.*, 2013). A soil pit the width of a seed drill (≈ 3m x 1.5m) is excavated perpendicular to tillage. Areas of different structure are identified in relation to horizontal layers formed by successive cultivations and lateral variation from wheels. Structure is described first by size and distribution of clods and from intra-clod porosity of clods >2mm. Le Profil Cultural not only includes structural unit morphology, but also the spatial variation of overall structure. Peigné *et al.* (2013) described further steps for assessing a compact transition layer between topsoil and subsoil and biotic activity.

The Whole Profile Method developed by Batey (2000) offers a holistic procedure for describing intrinsic soil quality and anthropic impacts on structure. The size and shape of aggregates, presence of pans, structural stability, clay mineralogy and evidence of compaction are evaluated (Batey, 2000). If required, Batey (2000) suggests the use of scoring systems described by Peerlkamp (1967) or McKenzie (1998). Principles developed by Batey form the basis of SOILpak, focused on structural characteristics associated with compaction and cotton growth (McKenzie, 1998). A soil pit, 1.5m deep and 4m long, perpendicular to tillage is recommended, from which five, 343cm^3 samples are extracted. Scores are assigned by firmness with clod size, shape, rupture resistance, aggregation within clods and intra-clod porosity examined. If structural scores are poor, overriding factors including interconnecting porosity, smeared layers or textural changes are visually assessed. Visual assessment of aggregate stability in water is scored from a dispersion test (Field *et al.*, 1997). The SOILpak procedure has been extended for a range of cropping systems and soils (Anderson *et al.*, 1998; McMullen, 2000).

SubVESS is an adapted version of VESS for subsoil assessment (Ball *et al.*, 2015) with an emphasis on identifying anthropic impacts on transition layers or compacted pans. Using a soil pit to 1.4m, soil layers are identified and assessed separately for mottling, strength, porosity, rooting and aggregate characteristics. "*Ssq* scores" are assigned for each layer using the SubVESS Flowchart, which provides a descriptive key and reference images. An overall *Ssq* score for the profile is expressed as a sequence of *Ssq* scores for individual layers from which any transition layer can be identified.

VSE Methodology

Evaluation criteria

All methods examine anthropogenic impacts on structure with some, mainly profile methods (Boizard *et al.*, 2005) additionally exploring intrinsic aspects. Aggregation (type, size and shape) and porosity form diagnostic criteria in almost all methods. Classification of the former generally assumes increased incidences of large (>5cm - >10cm), angular aggregates with higher rupture resistance, indicates poor structural quality (McKenzie, 1998; Guimarães *et al.*, 2011). Where desirable, differentiating anthropic impacts from intrinsic influences may be problematic.

Mueller *et al.* (2009) found that methods based on aggregation generated similar results, with strong correlations with measures of soil physical quality including bulk density (ρ_b) (Newell-Price *et al.*, 2013; Guimarães *et al.*, 2013; Mueller *et al.*, 2009), penetration resistance (Newell-Price *et al.*, 2013; Guimarães *et al.*, 2013) and air capacity (Mueller *et al.*, 2009). Additionally, VESS, largely dependent on aggregation diagnosis (Cui *et al.*, 2014), was related to soil respiration and enzyme activity (Cui *et al.*, 2015) along with chemical properties including, total carbon, soil organic carbon and total nitrogen (Askari *et al.* 2015).

Regarding aggregate determination, drop tests offer standardised, reproducible procedures of exposure. However, grass roots enmeshing aggregates (Pulido Moncada *et al.*, 2014a) and soils with high clay contents (Sonneveld *et al.*, 2014) were found to influence drop test results. Guimarães *et al.* (2011) found the manual exposure of aggregates generated the same overall results as drop-tests, despite being suggested as subjective (Ball *et al.*, 2007). Unless preformed on individual layers as the FAL method (Boizard *et al.*, 2005), drop tests do not allow the examination of aggregation within layers - a possible limitation (Giarola *et al.*, 2010; Guimarães *et al.*, 2011; Newell-Price *et al.*, 2013; Guimarães *et al.*, 2013). The delimitation of layers not only indicates potential soil functioning, but contextualises aggregation indicating anthropic influences. The evaluation of *in-situ* spatial arrangement, as employed by Le Profil Cultural, thoroughly indicates mechanisms or morphology of aggregation (Roger-Estrade *et al.*, 2004).

Both visual inter- (Shepherd 2000, Werner and Thämert 1989) and intra- (Guimarães *et al.*, 2011) aggregate porosity are examined. Exploring profile faces with a knife reveals macro-pores (Ball *et al.*, 2015), which can be highlighted with diluted paint (McKenzie, 1998). The quantification of earthworm burrows is also employed

(Munkholm, 2000; Peigné *et al.*, 2013). Mueller *et al.* (2009) found the VSA inter-aggregate porosity classification, assessed by examining an exposed face of a spade slice sample, correlated with dry ρ_b. VESS *Sq* scores, for which assessment of intra-aggregate porosity on exposed aggregate faces is required, corresponded with porosity determined by CT imagery (Munkholm *et al.* 2013; Garbout *et al.* 2013). The classification of clods described in Le Profil Cultural, based on intra-aggregate porosity (Peigné *et al.*, 2013), was justified with oedometer or consolidometer tests and significant differences between void ratios were reported (Roger-Estrade *et al.*, 2004). Le Profil Cultural modified for tropical soils (Neves *et al.* 2003) was found to relate to microbial biomass carbon (daSilva *et al.*, 2014).

Other criteria used include colour, redox morphology, smell and biological properties. However, techniques that include numerous, different criteria may generate the same overall result (Newel-Price *et al.*, 2013) suggesting that on certain soils, indicators additional to those centred on aggregation and porosity may be redundant. Mueller *et al.* (2009) suggested that where variation between structural states or evidence of compaction is not pronounced, procedures incorporating more diverse criteria (Shepherd *et al.*, 2000; Werner and Thämert, 1989) are desirable to achieve usable resolution. Relationships between diverse criteria and quantitative measurements were found. Pulido Moncada *et al.* (2014a) found the SQSP rooting criteria (Ball and Douglas 2003) correlated with ρ_b, soil organic carbon (SOC) and saturated hydraulic conductivity (K_{sat}), along with the VSA soil colour criteria (Shepherd, 2009) with SOC and K_{sat}. However, the site-specific nature of such relationships is emphasised (Mueller *et al.*, 2009). Indeed VSE indicates overall structural state (Munkholm, 2000; Newel-

Price *et al.*, 2013). Universal correlation between particular quantitative measurements and VSE criteria is not necessarily expected or desirable.

In addition to structural form, surface sealing (Shepherd, 2009; Ball and Douglas 2003) or dispersion tests (Beste, 1999; McKenzie, 1998) can indicate stability, while organic matter contents, soil texture, cracking, rooting and earthworm populations (Shepherd, 2009; McKenzie, 1998) indicate resiliency, thus holistically assessing structure (Kay, 1990).

Spatial, textural and moisture variation

Profile methods are efficient at distinguishing localised variation (Roger-Estrade *et al.*, 2004; McKenzie, 2001). Spade methods being quick, though less comprehensive (Boizard *et al.*, 2013), generate accuracy through replication over wide areas. At a field scale, sampling strategies vary (Cui *et al.*, 2014; Munkholm, 2000) and further attention to on-farm procedures (Askari *et al.*, 2013) regarding survey objectives is required. Recommended minimum numbers of samples range from four for VSA (Shepherd, 2010b) to ten for VESS (Ball *et al.*, 2007) with the avoidance of damaged areas, depending on objectives (Batey, 2000). Profile method soil pit excavation is perpendicular to tillage and sufficiently long to capture damaged areas and micro-variation (McKenzie, 1998; Peigné *et al.*, 2013). Additionally, pits can be located in two contrasting areas, capturing extremes of spatial variation within a field (Ball *et al.*, 2015; McKenzie, 1998). Sampling strategies at farm scale (Sonneveld *et al.*, 2014) have received limited attention.

Texture can influence diagnostic criteria, reducing precision. Batey and McKenzie (2006) mentioned differences in cracking and rupture resistance associated with cohesive, sandy and peaty soils. Texture can be dealt with by modifying the procedure or within classification systems. A modified VSA dropt test requires sandy and loam soil samples to be dropped from 0.5m instead of 1m (Shepherd 2009). Peerlkamp (1959) described different classification systems, with the poorest class featuring dense, smooth faced aggregates on clay and loam soils, and single-grain structure on sandy soils. However, consideration must be given to agricultural management capacity, as single-grain soils when irrigated, may be highly productive. Similar classification differences were outlined by Diez *et al.* (2012), McKenzie (1998) and Ball and Douglas (2003). The latter emphasised macro-porosity and soil colour assessment in fine-textured soils, as opposed to solely aggregation.

Relationships between moisture content and VSA, SOILpak (Murphy *et al.*, 2013) and VESS (Cui *et al.* 2014) have been described. Techniques recommend deployment on moist soils (Ball *et al.*, 2007; Boizard *et al.*, 2005; Ball and Douglas, 2003, Batey, 2000), with scientific studies conducted at near Field Capacity (Abdollahi *et al.*, 2015; Pulido Moncada *et al.*, 2014b). Clearly criteria such as rupture resistance will be affected by moisture content, Munkholm (2000) and McKenzie (1998) include different diagnostic descriptions for wet and dry soils. Some older methods described by de Boodt *et al.* (1967) also include procedures for dealing with moisture content. Research on the impact of moisture content on VSE criteria and deployment is limited.

VSE output

Batey (2000) emphasised the importance of describing structure rather than measuring it. Qualitative outputs, generally associated with profile methods (Peigné *et al.,* 2013; Batey, 2000) - reflecting their soil survey origin, provide detailed site-specific descriptive information, potentially lost when applying numeric scores. Qualitative descriptions may not be universally comparable (Batey, 2000) though this may not be desirable. Le Profil Cultural explores point specific morphology and causes (Roger-Estrade *et al.*, 2004) not necessarily applicable elsewhere. When summarising structural state, numeric scoring systems are regarded as important (Ball *et al.,* 2015; Ball *et al.,* 2013) as they quantify structural condition, are universally comparable and allow statistical analysis (Newell-Price *et al.,* 2013; Munkholm, *et al.,* 2013). Mueller *et al.* (2009) differentiated between techniques involving the assessment of properties either, concurrently or separately. The latter (Shepherd, 2000) might enhance reliability and objectivity (Mueller *et al.,* 2009) though may not to produce a summarising score (Ball and Douglas, 2003; Munkholm, 2000; Beste, 1999; Werner and Thämert 1989).

The Peerlkamp method, a concurrent type system, generated the same overall diagnosis as a complex multi-component system (Newell-Price *et al.*, 2013). However, its ten-point scoring system is criticised as being too broad, with a five-point index identified as optimal (Ball *et al.*, 2007). This can consist of three exclusive and two intermediate classifications (Beste, 1999), or five exclusive classifications, with non-integer intermediates possible (Guimarães *et al.*, 2011). In the case of VESS, the use of integer values can limit sensitivity and interpretation (Askari *et al.*, 2013), but deci-metric scores, derived by calculation from integer values requires expert diagnosis.

Additionally, integer values can be grouped into a simple “traffic-light” colour scheme (Ball *et al.*, 2007; McKenzie, 2013), clearly indicating structural state and potential remediation requirements.

Strengths, Weaknesses and Complimentary Aspects

In this section, only the most widely utilised methods are discussed.

Strengths and weaknesses

VSA includes a range of intrinsic characteristics of soil quality and of structural resiliency. The VSA drop test offers a clearly defined procedure for aggregate exposure, useful for non-experts, the later modifications of which account for texture variation (Shepherd 2009), originally found to be problematic (Newell-Price *et al.,* 2013; Giarola *et al.*, 2010). However, VSA does not delimit layers. VESS considers layers and focuses on anthropic impacts, relying on the manual exposure of aggregates. This requires some experience but still is suitable for non-expert use (Ball *et al.*, 2007). Despite being reported as not dependent on texture (Cui *et al.*, 2014; Guimarães *et al.*, 2013; Giarola *et al.*, 2013; Guimarães *et al.*, 2011), VESS was problematic with fine textured soils (Askari *et al.*, 2013), an issue that Ball *et al.* (2007) originally identified (Askari *et al.*, 2015). However, Pulido Moncada *et al.* (2014a) demonstrated that VESS generated similar results to VSA while taking less time.

SOILpak examines intrinsic soil quality along with structural stability and resiliency - notably vertical porosity highlighted with paint (McKenzie, 1998). Although possibly problematic on sandier soils (Boizard *et al.*, 2005), SOILpak not only includes different scoring procedures for different textures, but also descriptions of criteria at different moisture contents (McKenzie, 1998) while being suitable for non-expert use. In contrast, Le Profil Cultural, only applicable to arable soils, requires expertise (Roger-Estrade *et al.*, 2004) and is time consuming (Boizard *et al.*, 2005). However, it provides a comprehensive evaluation of structural morphology, notably impacts of tillage. Later descriptions (Peigné *et al.*, 2013) include criteria such as texture, cracking, and earthworm activity exploring vertical porosity, intrinsic quality, structural stability and resiliency. The analysis of clod morphology may indicate the latter (Boizard *et al.*, 2002). SubVESS, suitable for non-expert use, generates a relatively rapid evaluation of management below tillage depth. Issues may arise when differentiating anthropogenic from intrinsic features and when used on stony soils (Ball *et al.*, 2015).

Complimentary aspects

Profile methods examine point specific structural variation, assessing intrinsic quality and anthropic impacts, thus process interactions. VSA and VESS allow wider spatial evaluation and indicate structural state without thoroughly exploring mechanisms. Both approaches can be used together. SubVESS examines from 30cm depth and so should be used with VESS (Ball *et al.*, 2015). Specific technique methodology differs and can be complimentary. As Mueller *et al.* (2009) noted, where structural variation over wide areas is minimal, multi-component systems such as VSA, may be preferable over concurrent systems such as VESS. SubVESS, which places emphasis on aggregation and anthropic impacts (Ball *et al.*, 2015) worked well on a range of soil types, apart from a stony fine soil that was classified as *Ssq* 1 (good structural quality) despite being agronomically poor as indicated by Le Profil Cultural which considers intrinsic properties (Peigné *et al.*, 2013).

Conclusion

We show wide and growing evidence of the utility of VSE techniques. An appropriate method can be selected for all situations whether research, monitoring or management. Assessment objectives, the survey area and operators' level of expertise will dictate method selection. Profile methods allow a more detailed structural assessment than spade methods, but at the cost of coverage of within-field variation due to time constraints. However, both approaches offer information not attainable using quantitative measurements. Improvements required;

- The interaction between moisture content and VSE criteria appears to have received limited attention, while variation in soil texture presents problems for some procedures. Modified procedures or classification systems according to varying textures would be of benefit, notably to VESS. Nevertheless, research shows methods are robust and valuable.
- As the utility of VSE techniques has been established, we recommended exploration of sampling strategies and analysis of spatial variation. Minimum sample replication per method should be determined.

Further research is encouraged on new procedures and on less utilised existing methods. The latter may offer useful approaches to improve more widely adopted methods and to explore wider aspects of structure such as stability and resiliency, important for an integrated and holistic assessment, notably of agricultural soils.

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Table 1 Outline of VSE Spade Methods (Drop Test Procedures)

Method*	Origin	Objective	Land assessed	Characteristics assessed	Criteria employed	Depth assessed	Scoring system used	Intended users	Time requirement
The Diez Method (Diez *et al.*, 2012)	Germany	To assess structure in relation to soil functioning, notably plant growth and water infiltration	Emphasis on arable	Anthropic impacts on structure	Aggregate type, size, shape, inter-aggregate porosity, rooting, redox morphology, transition layer	40[b] cm	Score between 1 and 5 used *(1 = best, 5 = worst)*	Advisors and farmers[b]	- -
Visual Soil Assessment (VSA) (Shepherd, 2000, 2009, 2010)	New Zealand	To assess soil state, plant performance and the impact of farm management	Arable and grassland	Intrinsic soil quality and anthropic impacts on structure	Texture, aggregate size distribution, macro-porosity, redox morphology surface ponding and deformation, earthworms, smell, colour, potential rooting depth	Varying depths	*VS* score of between 0 and 50 *(<20 = poor, 20-35 = moderate, >35 = good)*	Advisors and farmers	40 minutes
FAL Method (Hasinger *et al.*, 2004)	Switzerland	To provide an accurate evaluation of structural state at a specific point[a]	Arable and grassland	Anthropic impacts on structure	Aggregate type, size, distribution and mean weight diameter[a]	45 cm	Score between 1 and 14 used for aggregate mean score *(1= worst, 14 = best).* Aggregate mean weight diameter is described in mm	Researchers and advisors[a]	90 minutes[a]

*Sources provided are not necessarily the original description of methods, [a] Sourced from: Boizard *et al.* (2005), [b] Points are of the authors' opinions

Table 2 Outline of VSE Spade Methods (Manual Aggregate Exposure Procedures)

Method*	Origin	Objective	Land assessed	Characteristics assessed	Criteria employed	Depth assessed	Scoring system used	Intended users	Time requirement
Spade Diagnosis (Görbing 1947)	Germany	To assess structure in relation to plant growth	Emphasis on arable	Anthropic impacts on structure	Aggregate size, shape, porosity and rooting	30 cm	No numeric scores used	Advisors and farmers	- -
Peerlkamp Method (Peerlkamp, 1959)	The Netherlands	To assess structure in relation to fertility, summarised by a single score	Emphasis on arable	Anthropic impacts on structure	Aggregate size shape, rupture resistance, inter- and intra-porosity, rooting, surface soil dispersion	15 cm	*St* Score between 1 and 10 *(1 = worst, 10 = best)*	Researchers, advisors and farmers[a]	30 minutes for 10 assessments[a]
The Werner Method (Werner and Thämert 1989)	Germany	To assess soil physical condition in relation to plant growth	- -	Anthropic impacts on structure	Layers, aggregate size, width, shape, inter-aggregate porosity, bio-pores	50 cm	Scores between 1 and 4 or 1 and 5 used to describe individual properties, resulting in a five digit nominal value score for each layer	Researchers	- -
Extended Spade Diagnosis (Beste, 1999)	Germany	To assess structure with regard to rooting conditions	Emphasis on arable	Anthropic impacts on structure	Aggregate type, size, shape, along with aggregate	40 cm	Scores between 1 and 5 used for structure and between	Advisors and farmers	- -

		and habitats for soil biota			stability		0 and 2 for silting type. Three sample layers are assessed separately		
Spade Analysis (Munkholm, 2000)	Denmark	To describe and relate soil tilth to management while aiding and evaluating soil management decisions	Emphasis on arable	Intrinsic soil quality and anthropic impacts on structure	Texture, colour, layer boundaries, aggregate size, shape, grade, soil consistence, macro-porosity, pore distribution, connectivity, orientation and rooting, OM decomposition and soil fauna	30 cm	Different scoring systems used for different properties, though no summarising numeric scores used	Researchers and advisors[a]	1 – 3 hours[a]
Soil Quality Scoring Procedure (SQSP) (Ball and Douglas, 2003)	United Kingdom	To assess physical fertility in terms of structure, rooting and soil surface conditions	Arable and grassland	Anthropic impacts on structure	Soil surface, aggregate type, size, shape, rupture resistance and rooting	30 cm	Three separate scores are assigned, each between 1 and 5 *(1 = worst, 5 = best)*	Researchers and advisors[a]	1 hour[a]
Visual Soil Structure Quality Assessment (VSSQA) –	United Kingdom	To semi-quantitatively assess soil structural quality in a	Arable and grassland	Anthropic impacts on structure	Aggregate size, shape, intra-porosity, rupture	25 cm	*Sq* Score between 1 and 5 *(1 = best, 5 = worst)*	Advisors and farmers	15 minutes

Visual Evaluation of Soil Structure (VESS) (Guimarães *et al.*, 2011)		manner accessible to non-experts			resistance rooting, redox-morphology				
Thinksoils Manual (Environment Agency, 2007, 2010)	United Kingdom	To assess soil structure with regard to erosion and run-off potential	Arable and grassland	Anthropic impacts on structure	Fissures and porosity, aggregate size, shape, rupture resistance, redox morphology, rooting, crop growth	40 cm	No numeric scores used	Advisors and farmers	- -

*Sources provided are not necessarily the original description of methods, [a] Sourced from: Boizard *et al.* (2005)

Table 3 Outline of VSE Profile Methods

Method*	Origin	Objective	Land assessed	Characteristics assessed	Criteria employed	Depth assessed	Scoring system used	Intended users	Time requirement
Le Profil Cultural (Peigné *et al.*, 2013)	France	To examine the impact of tillage on soil structure features	Arable	Emphasis on anthropic impacts on structure	Soil layers, structural zones, macro-pores, aggregate/clod size, intra-porosity, redox morphology, rooting	1.5 m	No numeric score used	Researchers	1 – 3 hours[a]
Whole Profile Assessment (Batey, 2000)	United Kingdom	To assess the anthropic impact on intrinsic soil properties in relation to crop growth[a]	Arable and grassland	Intrinsic soil quality and anthropic impacts on structure	Soil layers, texture, aggregate size, shape, aggregate stability, compacted zones, soil bearing capacity, soil colour, redox morphology	1.2 - 1.5 m	No numeric score used	Researchers and consultants[a]	20 – 40 minutes[a]
SOILpak (McKenzie, 1998)	Australia	To identify and assess compaction in relation to crop growth	Emphasis on arable	Intrinsic soil quality and anthropic impacts on structure	Texture, soil surface, rooting, aggregate size, shape, rupture resistance, macro-pores, aggregate stability	1.5 m	Score between 0 and 2 used for structural *(0 = worst, 2 = best)* and ASWAT score	Land surveyors, advisors and farmers	25 – 90 minutes[a]

							between 0 and 16 used for aggregate stability *(0 = negligible dispersion, 16 = serious dispersion)*		
SubVESS Flowchart (Ball *et al.*, 2015)	United Kingdom	To assesses any anthropogenic transition layer in terms of crop growth	Emphasis on arable	Anthropic impacts on structure	Redox morphology, porosity, rooting, aggregate size, shape	1.4 m	*Ssq* scores of between 1 and 5 *(1 = best, 5 = worst)*	Advisors	20 minutes

*Sources provided are not necessarily the original description of methods, [a] Sourced from: Boizard *et al.* (2005)